CONTINUOUS EXPLOSION-PUFFING OF APPLES

J. F. SULLIVAN, J. C. CRAIG, JR., R. P. KONSTANCE, M. J. EGOVILLE, and N. C. ACETO

ABSTRACT

The explosion-puffing process produces excellent dehydrated apple products that can be used as crisp snacks, instant applesauce, and ingredients for pies, tarts, and cobblers. To make these products more competitive and facilitate commercialization of the process, a continuous explosion-puffing system (CEPS) has been developed. The CEPS process has been optimized for orchard run Rome Beauty apples. Leaching loss as well as SO_2 absorbance and processing losses were determined. Drying profiles from a continuous belt drier were made. Pressure, temperature, and feed moisture were used as control variables for CEPS optimization studies. Analytical tests for bulk density, rehydration, color differences, percent disintegration, and hydroxymethylfurfural were performed on each sample. From these responses a bias was discovered, necessitating a second study. The second optimization study of these responses produced an optimal region. Any point in this region gives a value of pressure, temperature, and moisture. When these conditions are used for CEPS an excellent apple product results. Orchard run Winesap apples were processed through CEPS at an optimal condition determined for Rome Beauty apples to evaluate varietal differences. While their response was significantly different, the product was acceptable.

INTRODUCTION

APPLES are commercially dried into two marketable forms: "dried apples" (24% moisture) and "dehydrated apples" (3.0% moisture or less). Washington and California have produced an average of 5.1 million bushels or 2.14 million hundred-weights of dried apples annually from 1960 to 1973 (Duymovic, 1975; Huehn, 1975). One-third of this production was subsequently converted into "dehydrated apples."

"Dehydrated apples" have all the advantages of "dried apples" and none of the drawbacks. "Dehydrated apples" below 3% moisture and at 25°C or below retain their original flavor, color, and odor and have retained these qualities for as long as 3 yr (Smook and Neubert, 1950). "Dried apples," however, deteriorate in color and flavor and lose ascorbic acid, carotene, and sulfur dioxide unless held below 3.3°C.

The production of "dehydrated apples" is limited by the costly commercial drying methods (vacuum and freeze-drying) (Borgstrom, 1968) that are required. The explosion-puffing process developed at the Eastern Regional Research Center is a fast, inexpensive method of obtaining "dehydrated apples."

Explosion-puffing of apples is carried out after apple pieces have been dried to about 18% moisture (all moistures are on wet basis) by conventional hot air drying. Explosion-puffing is carried out in a gun (Heiland and Eskew, 1965) or in the Continuous Explosion-Puffing System (Heiland et al., 1977) at an elevated pressure and in a stream of superheated steam. The water within the partially dried pieces is rapidly brought to a temperature above its atmospheric boiling point. When the pieces are instantly returned to atmospheric pressure, a fraction of the water flashes into steam, creating a porous structure (Eisenhardt et al., 1962; Sullivan et al., 1977a). After being puffed, the apple pieces are dried by conventional means to 3% moisture or less. Explosion-puffing is the critical step in the process and restores the partially dried, concave, case-hardened (Potter, 1968) apple pieces to their normal size and shape but with a porous structure. This study was made to determine the effect of process variables in continuous explosion puffing on dehydrated apple pieces using that operation. Optimal conditions were determined for one batch of Rome Beauty apples, and the conditions were tested on a batch of Winesap apples. Losses were measured in the other process steps. The "explosion-puffing" dehydration process is diagrammed in Figure 1.

Authors Sullivan, Craig, Konstance, and Egoville are with the USDA Eastern Regional Research Center, SEA-AR, 600 E. Mermaid Lane, Philadelphia, PA 19118. Author Aceto is presently affiliated with Concentration Specialists, Inc., 26 Dundee Park, Andover, MA 01810.

EXPERIMENTAL

ORCHARD RUN, Rome Beauty apples from Eastern Pennsylvania were used in all but one experiment. The apples were mechanically peeled, cored, sliced, and cut lengthwise into 16 wedge shaped pieces and were then cut crosswise to produce 32 half segments. The segments were immersed for 5 min in a circulating solution of sodium bisulfite (1%) to bring the residual SO_2 concentration to about 7,500 ppm (moisture free basis (MFB)). The pieces were thoroughly rinsed over a shaker washer to help prevent adherence to each other during drying. This washing reduces the residual SO_2 to about 3,200 ppm. The segments were then dried in a continuous belt drier to predetermined moistures as the experiments required.

After drying the apple segments were coated with 0.75% monoglyceride to help prevent sticking. The monoglyceride has no effect on color, taste, or texture of the apple product.

Raw material testing

One hundred five bushels (2,000 kg) of apples were processed, and 13 experimental runs were made to follow the variations in SO_2 and total reducing sugar (TRS). Sulfur dioxide pickup and losses were determined from the peeling step to the final dried product

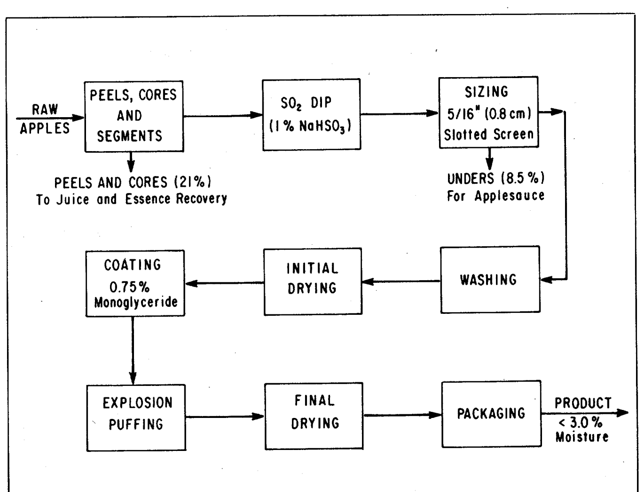

Fig. 1—Explosion-puffed "dehydrated apple" process.

but TRS values were obtained only through the initial drying step.

Drying studies

These studies report the difference in energy required to dry apple pieces by two processes (conventional and explosion-puffing) to 3% moisture. The study includes the determinations of moisture distribution and steam consumption in a two-stage multizone pilot scale continuous belt drier (Anon, 1963). This drier is a Sargent pilot plant research drier similar to their larger commercial driers. This drier was modified by adding doctor blades in the first and second zones to improve drying (Sullivan et al., 1977b). Figure 2 shows two curves (obtained with and without doctoring), both indicating apple piece temperature (thermocouple measurements) during drying in Stage 1. Curve 1 indicates the temperature of the apples when doctoring was used. The doctored apples dried faster and approached the dry bulb temperature of the drier sooner. Apple piece moistures were found to be more homogeneous after doctoring. For these reasons doctoring was used in all subsequent experiments.

Two moisture distribution drying experiments were made. In the first, apple slices were dried to explosion-puffing moisture ca. 18.5% and the second to a "dehydrated apple" moisture ca 3.5%. Samples were taken at the centerpoints of each zone, and before and after drying. Drying to these two different moistures required changing belt speeds. Other drying conditions were held constant for these experiments. They were: air velocity 3.0 m/s; direction of air flow downward; stage 1 temperature 82.2°C; stage 2 temperature 73.8°C, and bed depth entering stage 1, 5 cm.

Steam usage was determined for each stage by passing steam condensate through separate heat exchangers. The condensate was collected during a measured time period and weighed.

Testing the continuous explosion-puffing system (CEPS)

Capacity determination. Apple half segments, 15% moisture, were fed to CEPS (Heiland et al., 1977) at various rates. The segments were conveyed to the feed chamber of CEPS (volume 0.068 m^3) which was set to open every 20 sec. After each closing, the pressure in the feed chamber was brought up to the main chamber pressure within 2 sec, then the apple pieces in the feed chamber were discharged to the main chamber and onto the transfer belt. As the feed rate increased, the feed chamber and the transfer belt in the main chamber became vulnerable to overloading. Both areas were carefully monitored during the test.

Optimization

Optimization study #1. Over a 4-yr period, experiments were carried out to determine the effect of initial moisture (M), internal pressure (P), and temperature (T) on partially dried apple pieces in CEPS as reflected in the final product. These experiments were made to establish the optimum operating conditions of CEPS. Apples used were harvested during 1975, 1976, 1977, and 1978 (Table 1). The feed rate was 68 kg/hr for each test. After being explosion-puffed, all samples were dried to 2–3% moisture in a hot air tray drier and evaluated.

The chemical and physical attributes evaluated were: bulk density, rehydration, percent disintegration, color difference, and hydroxymethylfurfural (HMF). These properties were chosen because they most clearly reflected the quality of the explosion-puffed product. Fast rehydration or water pickup is a desired characteristic of explosion-puffed material. The greater the puff, the more porous the product, and the more readily the water is picked up, as reflected by rehydration values. Bulk density decreases during explosion-puffing, and should be between 160 and 128 kg/m^3; a value higher than this is indicative of an inadequate puff; lower, the product is overpuffed causing excessive breakage. Minimal disintegration is desired. HMF and color difference values relate to eye appeal and flavor. Generally, as these products brown they become less desirable. In color determinations, scales developed by Hunter (Hunter, 1942) were used. They are "R_d," "a," and "b." "R_d" measures the reflectance of the sample, "a" signifies redness if positive and greenness if negative, and "b" signifies yellowness if positive and blueness if negative. In the apple experimentations "a" but not "R_d" or "b" varied with operating conditions and correlated with them. Therefore, "a," the meaningful color difference measurement, was utilized. Methods used for these determinations are explained under analytical procedures.

Optimization study #2. A more limited study was made in optimum study #2 by the use of an experimental design of 15 conditions which included four levels of moisture (11.5–16.5%), five levels of pressure (62–124 kPa), and five levels of temperature (154–185°C). The apples used were from the batch harvested in 1978. The design was replicated three times. A bias present in the first optimal study from rewetted material was eliminated. The samples from this design were dried and evaluated as in the first study.

Effect of variety. The result of optimum study #2 (Rome Beauty Apples) was extended by testing it with Winesap apples. Winesaps were also compared in quality to Rome Beauties. The Winesaps were processed by (1) selecting a condition of pressure, temperature, and moisture within the optimal range for Rome Beauties, (2) drying apple pieces to the selected moisture (18.0%), and (3) processing these apples through CEPS at the selected internal pressure (95 kPa) and internal temperature (168°C). Values from the Rome Beauty design of bulk density, rehydration, percent disintegration, HMF, and "a" (color determination value) were calibrated for the specified conditions of pressure temperature and moisture. After being processed through CEPS, the Winesap apple pieces were dried, and the product characteristics were determined and compared to the predicted values of the Rome Beauties.

Steam usage. Steam consumed by CEPS during its operation was determined by flow meters. Flow rates were obtained by the use of steam turbine flow meters (Anon, 1976). The meters were located in the two steam inlets and in one of the two exhausts. Steam exhausting during explosion-puffing could not be measured but was calculated by difference. The steam turbines had been calibrated by collecting and weighing condensate prior to the experiments.

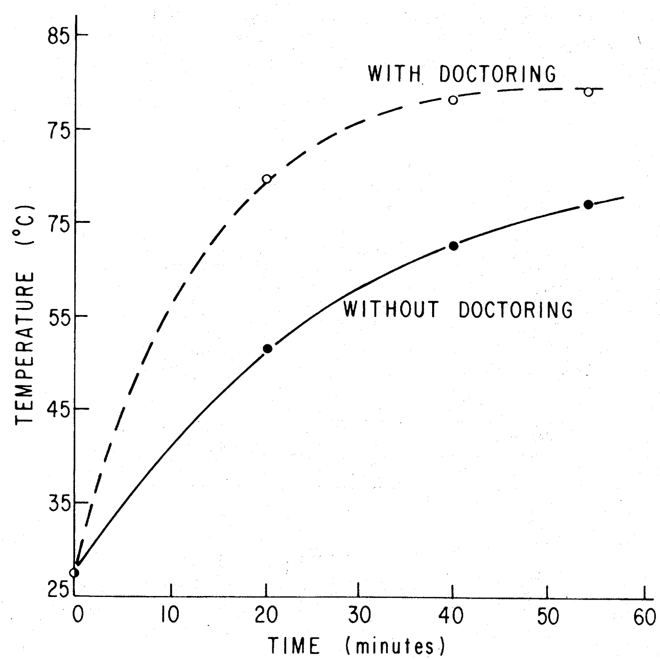

Fig. 2—Doctoring study in stage one of continuous belt dryer at 82.2°C.

Final drying time determination

There was never a sufficient quantity of apples to determine the steam consumption during final drying in the continuous belt drier. An alternate method was used to simulate this processing step in this drier. To do this, a National tray drier was used in which smaller

Table 1—Experiments of optimization study #1

Year harvested	Pressure kPa Range	Pressure kPa No. of levels	Moisture % Range	Moisture % No. of levels	Temperature °C Range	Temperature °C No. of levels
1975	55–138	4	10.0–22.0	5	160	1
1976	55–103	3	10.0–21.0	4	160–190	3
1977	55–103	3	10.0–17.0	4	120–160	2
1978	62–124	5	11.5–18.0	6	155–185	6

drying lots could be compared. Apple pieces that had been dried to 13% moisture (wet basis) were used. Some of the same apples were explosion-puffed in CEPS. Their moisture increased to 17%. Equal weights of the explosion-puffed (17%) and conventional pieces (13%) were dried in the National drier to below 3% moisture. Weighings were made during the dryings at timed intervals until the products reached a constant weight. Drying curves were constructed based on the final moisture of each product and the difference in drying rates was determined. From this information, the simulated final drying time for the explosion-puffed apples in the continuous belt drier was determined.

Energy evaluation (Steam usage)

The total energy from steam consumption for the Explosion-Puffing Dehydrated Apple Process was determined from three steps: initial drying, CEPS, and final drying. Steam consumption while drying in the continuous drier was determined by weighing condensate for timed intervals. Steam used in CEPS was ascertained from the steam turbine flow meters.

Analytical procedure

Reconstituted apples at room temperature were used for determining hydroxymethylfurfural (HMF), color, and total reducing sugars (TRS). Moisture content, bulk density, rehydration, disintegration, and SO_2 analysis started with "dehydrated" apple slices.

Total reducing sugars (TRS). TRS were determined by the colorimetric method of Ting (1956).

Sample preparation was dependent on the moisture content of the apple. Fresh apples were peeled, cored, and pureed in a blender and the juice was squeezed through cheesecloth and then centrifuged. Dried or partially dried apples were reconstituted to fresh apple and the above procedures were followed.

An aliquot of the centrifuged juice was clarified with neutral lead acetate. Excess lead was precipitated by the addition of sodium oxalate. A portion of this clarified filtrate was used for the colorimetric analysis.

Hydroxymethylfurfural. HMF was determined by Method II of Winkler (1955) with modifications.

A 5.5-g sample of ground dried apple pieces was blended with 125 ml hot deionized H_2O for 5 min. With partially dried apples, 10.0g of diced apple pieces was blended with 125 ml hot deionized H_2O for 10 min. The blend was made to 250g and centrifuged for 10 min. The supernatant was filtered through filter paper and a 10.0 ml aliquot was analyzed by the Winkler Method II. Results are reported as mg HMF per 100g of fresh apple.

Color measurement. A Gardner Automatic Color Difference Meter was used for all color measurements. The reconstituted apples were placed in glass cells, and color values for each sample were obtained as Hunter a, b, and R_d units. The instrument was standardized each time with a standard color tile #CLY 0032 (R_d = 60.8; a = −1.8; b = +22.7).

Moisture. Moisture content was obtained by the standard vacuum oven method. All samples were dried at 70°C under vacuum for 16 hr. Results are expressed on a wet basis.

Sulfur dioxide (SO_2). Sulfur dioxide was determined by the method of Nury et al. (1959) with modifications.

A 15-g sample was extracted with a mixture containing 45 ml of a special buffer solution (Ross and Treadway, 1960) plus 240 ml of distilled water.

An aliquot of the blend was weighed into a tared 100 ml volumetric flask, then 2 ml of 0.5N NaOH was added. The solution was swirled 30 sec, permitted to stand an additional 1-1/2 min, then 2 ml of 0.5N HCl was added. Then 20 ml of sodium tetrachloromercurate solution containing sulfamic acid (0.60g/L) was added to prevent interference by nitrogen dioxide (West and Ordoveza, 1962). The mixture was diluted to 100 ml with water, then mixed and filtered. Two ml of the filtrate was used for the colorimetric analysis.

Disintegration. Percent disintegration was determined by manually separating disintegrated pieces in a 100-g sample and weighing this portion.

Rehydration. A 25-g sample was boiled in water 5 min, then drained and weighed. The amount of water picked up per gram of dry solids was determined by subtracting the original sample weight (25g) from the weight of the rehydration and dividing this weight by the solids in the 25-g sample.

Bulk density. Bulk density was determined by filling a tared crystallizing dish of known volume with dried apple pieces then weighing the apples and determining the weight per volume.

Table 2—Total reducing sugar (TRS) and SO_2 determinations for 13 runs

	% Moisture[c] (Wet basis)	g TRS/100g[c] raw apples	TRS loss %	SO_2 ppm
After peeling	87.22 ± 0.49	6.87 ± 0.56	–	–
After 5 min circulation (1% SO_2)	88.84 ± 0.40	6.08 ± 0.57	11.6	7,350
After wash	88.89 ± 0.38	5.93 ± 0.21	2.2	3,150
After drying	23.78[a] ± 4.04	5.47[b]	6.7	533[a]
Apple at 3% moisture	1.74[a]	–	–	47[a]

[a] Eight determinations
[b] Two determinations
[c] 95% Confidence limit

Table 3—Dryer steam usage

	Steam rate		Drying time	
Final moisture	Stage 1 kg/hr	Stage 2 kg/hr	Stage 1 hr	Stage 2 hr
ca 3.0%	350	150	2	14
ca 18.0%	377	161	1	1

RESULTS & DISCUSSION

Raw material experiments

Apple half segments (pieces) absorbed water during the pretreatment steps of sulfiting and washing and also lost sugar through leaching (Table 2). The sugar leaching losses of 11.6% are in agreement with the work of Mylne and Seegmiller (1950). A 2.2% loss of sugar resulted from washing and an additional 6.7% was lost during initial drying. Additional reducing sugar losses were prevented by the amount of SO_2 in the pieces (3,150 ppm).

Sulfur dioxide was readily absorbed by the apple pieces (Table 2), but 58% was lost during the washing step. However, the amount of SO_2 retained (3,150 ppm) suppressed the nonenzymatic browning (Resnik and Chirife, 1979) during the remaining processing, i.e., initial drying, explosion-puffing, and final drying. Forty to 60 ppm SO_2 was present in the "dehydrated apples" and was adequate to maintain color and flavor at 3.3°C.

Drying studies. Figure 3 depicts the two-stage, multizone drier. Sample points are indicated and moisture and their confidence limits (95%) are shown for eight experimental runs. Two hr and 25 min were required to dry 88 kg to 23.8 ± 4.6% moisture. Belt speeds to achieve this drying time were 5.1 cm/min first stage, and 4.2 cm/min second stage. Steam condensate was collected from the first and second stages and weighed during times intervals while the stages were under a full drying load. Steam usage rates were determined (Table 3).

Apple pieces were dried at slower belt speeds: 2.9 cm/min first stage and 2.7 cm/min second stage to simulate a "dehydrated apple" product without explosion-puffing to obtain steam usage rates. Steam condensate was collected and weighed during timed intervals and a usage rate was determined (Table 3). The apples for these tests were dried above the "critical" temperature (74°C) for apples (Jacobs, 1951); thus the product was off-color. Lower temperatures and much longer drying times would be required to dry apple pieces to approach 3.0% moisture with good color and flavor.

From Table 3 the amount of steam used for drying in

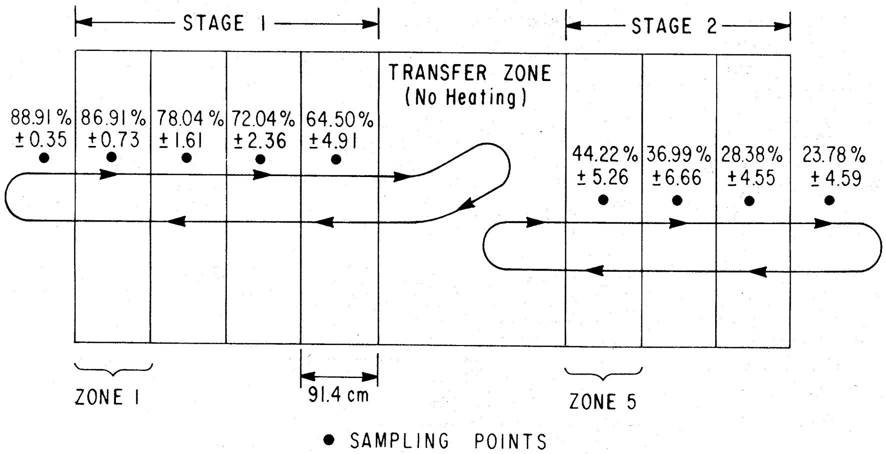

Fig. 3—Moisture distribution of apple pieces before, during, and after drying in continuous belt dryer.

each stage at the two drying conditions can be calculated. The total steam is determined by multiplying the drying time required for each stage by a steam rate for that stage. From the amount of steam and the line pressure, energy consumption was calculated.

Testing the continuous explosion-puffing system

Capacity determination. There are two low volume areas in CEPS that can restrict feed, namely the feed chamber and the channel above the transfer belt. Partially dried apple pieces were fed to CEPS at increasing rates from 140 kg/hr to 225 kg/hr. At the rate of 225 kg/hr the apples overfilled the transfer belt below the feed chamber and were not fully moved away befor the next discharge. This caused a blockage, and the apple pieces backed up through the feed chamber; however, CEPS functioned normally at feed rates of 195 kg/hr and lower.

Optimization study #1. The results of these experiments (responses) were related to the three controlled variables by simple quadratic equations. In most cases, 2-factor interactions were found significant, and thus were included. Approximately 500 data points, including within season replicates, were utilized. Table 4 shows the responses and results of the regressions.

An extensive analysis of residuals (predicted-observed) revealed a number of apparent biases which have not been explained. However, one critical experimental bias was uncovered. When drying to various moisture levels for testing, apples to be processed at a particular moisture sometimes were overdried. These moistures were corrected by the addition of water to that batch, and time was allowed for equilibration. On analysis of the residuals, it became evident that these samples formed a separate population. Consequently, the model developed was used solely to define an approximate optimal region. A new, definitive, experimental design was prepared with the criterion that the design would be near and around the estimated optimal region. All apples for this design were dried directly to the experimental moistures.

Optimization study #2. Results of regressions on this data are shown in Table 5. Quadratic equations, including 2-factor interactions, were fitted to data for each response. These equations were used to provide a set of constraints on the product. Table 5 shows the upper and lower limits for each response. On the application of an optimization routine, it was found that no constraint was "controlling," i.e., a feasible region of operation was found, wherein all constraints could be satisfied, according to the prediction equation. Figure 4 shows a typical case, at a fixed moisture level. Note that three different responses are constraining in different operating regions. No practical purpose would have been served by further narrowing the constraints, so the recommended operating conditions are offered as the center of the optimal region, generated by taking the centroids of successive constant moisture plots (Fig. 5). One advantage to this is that the operator need not dry to a given moisture exactly,

Table 4—Results of regressions optimum study #1

Y*	R^2 **
Bulk density	0.840
Rehydration	0.741
"a"***	0.553
% Disintegration	0.674
HMF	0.825

* $Y_k = c_{0k} + \sum_{i=1}^{3} c_{ik}X_i + \sum_{i=1}^{3}\sum_{j=1}^{3} c_{ijk}X_iX_j$

** (Multiple correlation coefficient)^2

*** One of the color difference measurements

Table 5—Multiple correlations and coefficients of apple model for optimum study #2

Model form: $Y = c_0 + c_1 P + c_2 T + c_3 M + c_4 PT + c_5 TM + c_6 PM + c_7 P^2 + c_8 T^2 + c_9 M^2$

Y	Bulk density	Rehydration	"a"	% Disintegration	HMF
R^2	0.851	0.852	0.759	0.591	0.737
Upper and lower limits	10.* (160.2 kg/m^3) 8.* (128.1 kg/m^3)	5 3.8	5 3	5 2	11 10
c_0 **	61.080	−12.355	−20.466	38.051	387.611
c_1	−1.876	1.106	1.069	0.070	−4.937
c_2	−0.171	0.137	0.181	−0.378	−2.307
c_3	−0.672	−2.091	−1.522	3.582	3.660
c_4	−0.00180	−0.00239	−0.00463	0.00235	0.02043
c_5	0.00254	−0.00013	0.00486	−0.01107	−0.01879
c_6	−0.05292	0.00236	0.01806	−0.41986	−0.20153
c_7	0.10548	−0.00238	0.00311	0.20852	0.06954
c_8	0.00020	−0.00015	−0.00031	0.00075	0.00356
c_9	0.02194	0.06558	−0.00949	0.19397	0.16660

* Pounds per cubic foot was used in this correlation.

** Sufficient significant places are provided so that the reader can recalculate the response surface. No unexpected precision should be inferred.

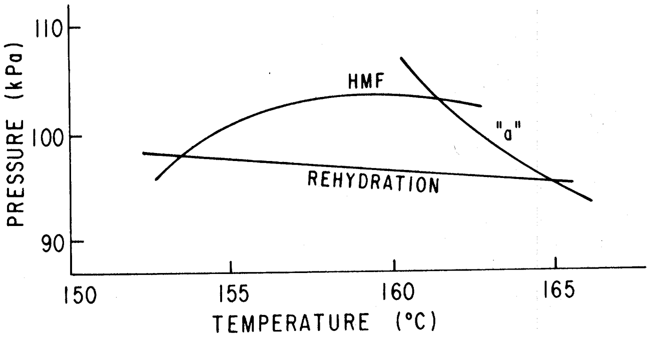

Fig. 4—Optimization area at 14.5% moisture.

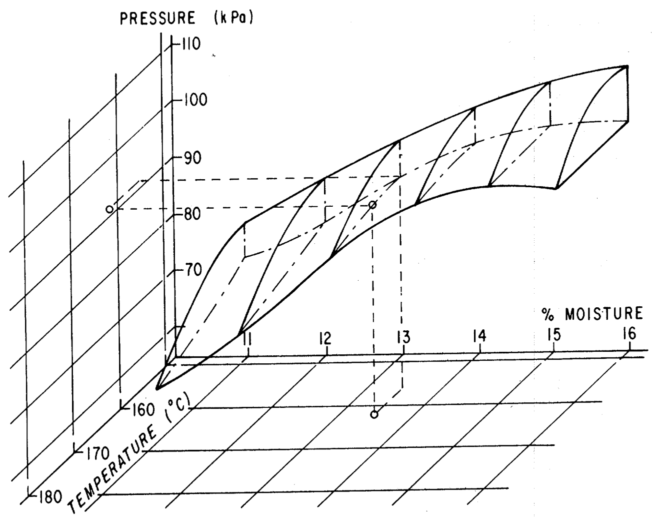

Fig. 5—Constraining response surfaces for optimal region.

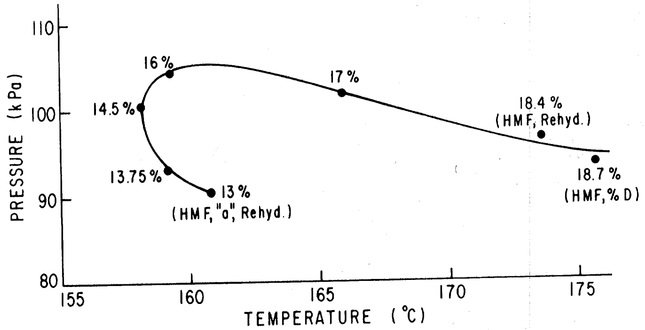

Fig. 6—Center points of centroids at fixed moistures.

Table 6—Chemical and physical property values

Property	Predicted (Rome Beauty)	Experimental (3 Runs) (Winesap)
Bulk Density kg/m^3	117.0	147.0
Disintegration %	3.8	5.3
"a"	– 3.1	– 3.2
Rehydration g H_2O pickup/g dry solids	3.89	4.84
HMF mg/100g	10.66	17.36

but can choose a point on the centroid line (Fig. 6) corresponding to his achieved moisture.

Effect of variety. The predicted responses for the Winesap apple (solids 15.1% fresh weight basis) from the Rome Beauty apple (solids 12.7% fresh weight basis) design and the Winesap experimental values are shown in Table 6. The bulk density reflects the amount of volumetric change effected in the piece during processing. However, the Winesap fresh solids content was higher than the Rome Beauty. While the bulk density experimental value does not appear to confirm the predicted value, if the Winesap value is put on the same solids basis as the Rome Beauty apple it would be 121 kg/m^3. The predicted and experimental values for percent disintegration and "a" are within experimental error.

The HMF value for Winesap apples was 10.30% before explosion-puffing, and the experimental value (Table 6) after explosion-puffing was 17.36%. The HMF value for Rome Beauty apples was 6.78% before explosion-puffing and the predicted value after explosion-puffing was 10.66%. The higher HMF values shown for the Winesap apples may have been due in part to the higher level of reducing sugars. The total reducing sugars (fresh weight basis) for the Winesap were 7.63% compared to 6.70% for the Rome Beauties.

The rehydration value of the Winesap was well out of the Rome Beauty range. The dehydrated Winesap apple pieces were excellent in texture, had the typical Winesap sweet tart taste, and possessed a slight yellow hue.

Steam usage. CEPS was operated at optimal conditions as determined from study #2 for three runs (replicates). The conditions used were: moisture 18%; pressure 95 kPa; and temperature 168°C. At these conditions, a total of 63.6–68.2 kg/hr of steam was used, 56.8 kg/hr to superheat the main chamber and 11.4 kg/hr to supply the energy to explosion-puff. For the three runs, 40.2 kg of partially dired apples were processed in total time of 22-1/3 min and used 25.3 kg of steam (27.7 X 10^6 Joules).

Final drying time determination. The drying time in the continuous belt drier to dry 64.7 kg of conventional apple pieces to 3% moisture was 16 hr (Fig. 7). The total drying time for the explosion puffing process had to be determined in two steps: (1) the time it took to dry to 13% moisture in the continuous belt drier (2 hr) plus (2) the final drying time which had to be estimated.

The final drying time was simulated by drying conventional and explosion puffed apples in a National tray drier and comparing drying rates. Equal weights of conventional apples (13.0%) and explosion-puffed apples (17.0%) were dried to below 3% (Fig. 8) and their drying times were compared (105.3 min to 41.3 min, respectively). The explosion-puffed apple pieces dried 2.55 times as fast as the con-

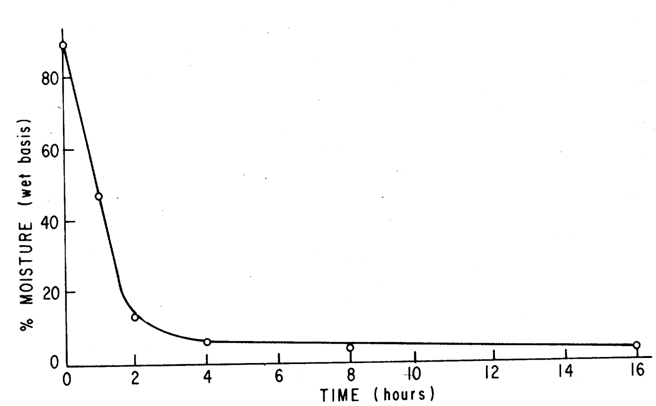

Fig. 7—Drying curve for conventional dried apple pieces.

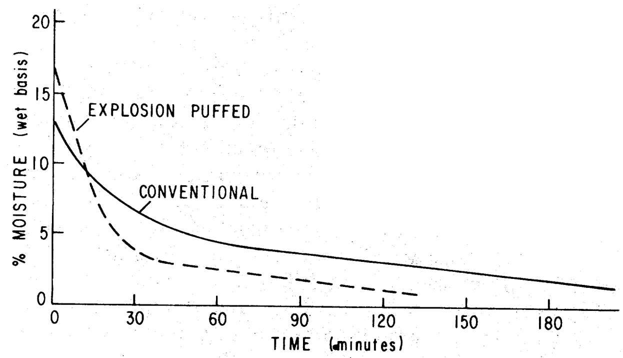

Fig. 8—Final drying curve of explosion-puffed apple pieces and corresponding drying curve for conventional apple pieces.

ventional pieces in the tray drier. We assumed this rate to hold for the continuous belt drier. Therefore, if the conventional apples take 14 hr to dry from 13% to 3%, then the explosion-puffed apple can be estimated to require 5.5 hr to dry from 17% to 3% in this drier. The total drying time for the explosion-puffed apples in the continuous belt drier was 2 hr plus 5.5 hr or 7.5 hr for 64.7 kg of apples (starting weight).

Energy evaluation (steam usage). The total amount of energy used in the explosion-puffing process was determined in three steps; (1) from steam used in initial drying, (2) from steam used in explosion-puffing, and (3) from steam used in final drying.

(1) *Energy used in initial drying.*
2 hr (initial drying time) × 376.8 kg/hr steam (Table 3)
or 753.6 kg of steam at 896.3 kPa 1.53×10^9 joules

(2) *Energy used in explosion-puffing* (operational time 0.17 hr).
68.2 kg/hr × 0.17 hr equals 11.8 kg of steam;
11.8 kg of steam at 172.4 kPa (130.7°C) equals 0.025×10^9 joules
11.8 kg of steam at 130.7°C raised to 218.3°C 0.002×10^9 joules

(3) *Energy used in final drying.*
Final drying time (estimated 5-1/2 hr)
5-1/2 hr (final drying time) × 161 kg/hr steam (Table 3)
or 886.6 kg of steam at 896.3 kPa 1.79×10^9 joules

Total energy used for the explosion-puffing process
(1 + 2 + 3) 3.35×10^9 joules

The steam used to dry 64.7 kg to a final weight (10 kg) by conventional air drying took 16 hr; 2 hr in the first stage and 14 hr in stage two.

(1) *Energy used in first stage.*
2 hr × 350 kg/hr steam (Table 3)
or 699.2 kg of steam @ 896.3 kPa 1.42×10^9 joules

(2) *Energy used in second stage.*
14 hr × 150 kg/hr (Table 3)
or 2097.2 kg of steam at 896.3 kPa 4.24×10^9 joules

Total energy used (1 + 2) 5.66×10^9 joules

CONCLUSIONS

AN EXCELLENT "dehydrated apple" piece (<3.0% moisture) can be made by the explosion-puffing process. The product retains characteristic taste and texture. In that regard, it is notable that there was an evident difference in flavor between products from Rome Beauty and Winesap apples. The product can be eaten dry, as a crisp snack, or can be rapidly reconstituted for use in pies and tarts.

An optimal operating region was determined for Rome Beauty apples. It appears to be insensitive to yearly variation in raw material and offers a range of operating condition combinations which will produce desirable products with minimal losses. While it should not be assumed that the optima specified are exactly correct for other varieties and growing areas, a test on Winesap was encouraging, as it is a substantially different apple variety. The product was acceptable, implying that optimal operating conditions for the Winesaps are near, and could be easily established. Obviously, processing other varieties would also require some modification of operating conditions, but the general interaction of process variables should hold. For Rome Beauties, at least, process control requirements were not stringent.

Sugar leaching losses were not excessive, but the SO_2 losses were high. Some of the SO_2 losses can be attributed to heat of volatilization but most losses result from Maillard reaction occurring during processing (McWeeny et al., 1964). High losses of vitamin C can be expected because of high processing temperatures.

Drying was made more efficient by pre-washing and doctoring because the apples were dried as individual segments rather than a solid slab. The washing step reduced the initial tendency of the apple pieces to cohere, and the mixing and scraping action during doctoring sped the drying of the surfaces sufficiently to prevent sticking to the drier belt and to themselves.

Drying efficiency can be increased by obtaining moisture profiles throughout the drier at various drying temperatures and belt speeds. Each drying zone can then be set to obtain maximum drying at the lowest temperature.

A 44% reduction in steam consumption was realized when the explosion-puffing process was used to dehydrate apple pieces rather than conventional dehydration. This reduction can be attributed to the time saved drying apple pieces from about 20% moisture (wet basis) to less than 3%. Because explosion-puffing imparted a porous structure to the apples, these pieces dried 2.1 times faster than apple pieces dried by the conventional hot air method.

REFERENCES

Anon. 1963. "A Basic New Concept in Pilot and Research Equipment." C.G. Sargent's Sons Corp., Graniteville, Mass.

Anon. 1976. Technical Manual Installation and Operation Manual No. 312-3(B) and Manual No. 511-1. ITT Barton, P.O. Box 1882, City of Industry, Calif. 91749.

Borgstrom, G. 1968. "Principles in Food Science," Vol. 2. p. 306. The Macmillan Company, New York, N.Y.

Duymovic, A.A. 1975. Processed Apple Utilization Trends-Outlook and Competition on the Domestic Markets. Third National Processed Apple Conference, Geneva, N.Y.

Eisenhardt, N.H., Cording, J. Jr., Eskew, R.K., and Sullivan, J.F. 1962. Quick-cooking dehydrated vegetable pieces. Food Technol. 16(5): 143.

Heiland, W.K. and Eskew, R.K. 1965. A New Gun for Explosive-Puffing of Fruits and Vegetables. U.S. Agr. Res. Serv. ARS 73-47, 8 pp.

Heiland, W.K., Sullivan, J.F., Konstance, R.P., Craig, J.C. Jr., Cording, J. Jr., and Aceto, N.C. 1977. A continuous explosion-puffing system. Food Technol. 31(11): 32.

Huehn, W.G. 1975. A Producer's View—Problems and Priorities. Third National Processed Apple Conference, Geneva, N.Y.

Hunter, R.S. 1942. Photoelectric tristimulus colorimetry with three filters. Natl. Bur. Standards, Circ. 0429, U.S. Government Printing Office.

Jacobs, M.B. 1951. "The Chemistry and Technology of Food and Food Products," p. 572. Interscience Publishers Inc., New York, N.Y.

McWeeny, D.J., Moody, J.P., and Burton, H.S. 1964. The penetration by and distribution of calcium and bisulphite ions during potato scalding and hot-air dehydration. J. Sci. Food Agric. 15(4). April.

Mylne, A.M. and Seegmiller, C.G. 1950. Laboratory studies on factors affecting leaching losses during the processing of apples.

Food Technol. 4(2): 43.
Nury, F.S., Taylor, D.H., and Brekke, J.E. 1959. Modified direct colorimetric method for determination of sulfur dioxide in dried fruits. J. Agric. Food Chem. 7: 351.
Potter, N.N. 1968. "Food Science," p. 238. The Avi Publishing Co., Inc., Westport, Conn.
Resnik, S. and Chirife, J. 1979. Effect of moisture content and temperature on some aspects of non-enzymatic browning in dehydrated apple. J. Food Sci. 44(2): 601.
Ross, L.R. and Treadway, R.H. 1960. A rapid method for the determination of sulfur dioxide in sulfited pre-peeled potatoes. Amer. Potato J. 37: 102.
Smook, R.M. and Neubert, A.M. 1950. "Apples and Apple Products," p. 295. Interscience Publisher Inc., New York, N.Y.
Sullivan, J.F., Konstance, R.P., Aceto, N.C., Heiland, W.K., and Craig, J.C. Jr. 1977a. Continuous explosion-puffing of potatoes. J. Food Sci. 42(6): 1462.
Sullivan, J.F., Konstance, R.P., and Heiland, W.K. 1977b. Doctoring and drying method. U.S. Patent 4,031,252.
Ting, S.V. 1956. Rapid colorimetric methods for simultaneous determination of total reducing sugars and fructose in citrus juices. Agri. & Food Chem. 4: 263.
West, P.W. and Ordoveza, F. 1962. Elimination of nitrogen dioxide interference in the determination of sulfur dioxide. Anal. Chem. 34: 1324.
Winkler, O. 1955. Beitrag zum Nachweis und zur Bestimmung von Oxymethylfurfural in Honig und Kunsthonig. Z. Lebensm.-Untersuch und Forschung, Bond 102, Heft 3.
Ms received 2/2/80; revised 4/26/80; accepted 5/4/80.

The authors thank Pauline E. McDowell and Ruth Campbell for their chemical analyses; Susan Leiby, Kevin Kelly, and Carlisle Ross for their technical assistance, and Florence B. Talley, Food Technologist, for aiding in flavor detection and color evaluations.

Reference to brand or firm name does not constitute endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.